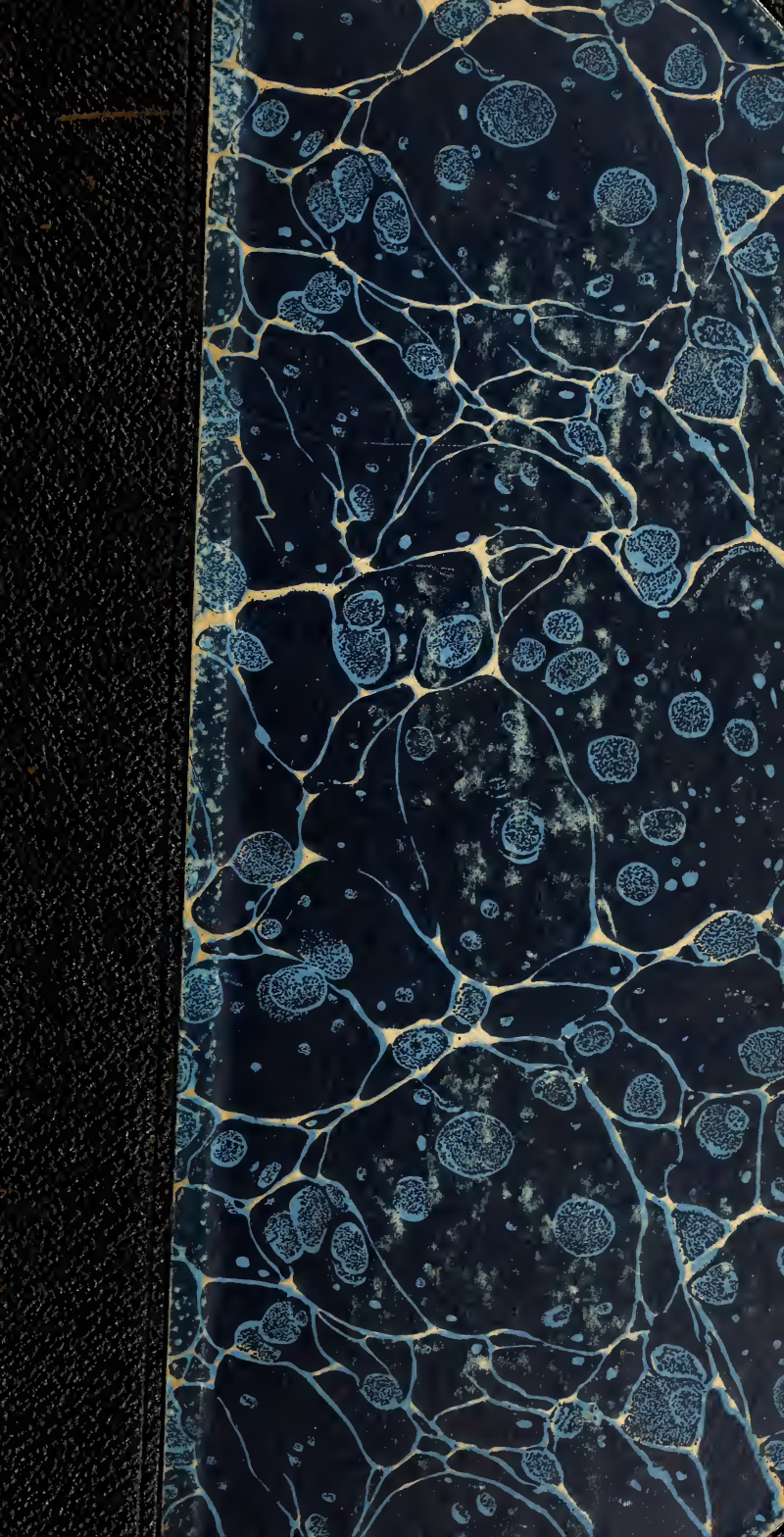

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WATER-STRESS BEHAVIOR OF PIMA COTTON IN ARIZONA.

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SCOPE OF THE INVESTIGATIONS.

American Egyptian long-staple cotton, which was first grown commercially in 1912, is now one of the principal crops of Arizona and portions of California. In 1920 approximately 250,000 acres were planted to this crop in the States mentioned. The acreage planted to the Pima variety of American Egyptian cotton in the Salt River Valley far exceeded that of any other crop in 1920.

An investigation of the practicability of using soil-moisture determinations as an index of the water requirement for growing Pima cotton was begun in 1918 and continued through the year 1919, in the belief that definite information would be of value in determining the best methods of irrigation, which is a very important feature in the production of the crop. The plan in 1919 was to apply water so as to keep different amounts of moisture available at various depths of soil and to study the behavior of the plants in response to the different proportions of soil moisture, in order to learn the quantity of water that would give the best development of the crop. This bulletin relates to the data obtained in 1919, after the experience of the previous year had demonstrated that it was possible to control

fairly accurately the amount of moisture in the soil by applying measured quantities of water at times when it was indicated by soil-moisture determinations that the moisture content had been depleted to the minimum point desired.

Although the experiments were not carried to the point of demonstrating a satisfactory method that could be recommended for general practice, it is believed that some of the data are of sufficient importance to be made available for other experimenters and for the interested public. As a result of these and other experiments it is now believed that the behavior of the plants will serve as a practical guide in judging the need of irrigation, making unnecessary the determinations of the moisture content of the soil except in critical cases.

Certain phenomena were noted in regard to the water relations of the different sizes of plants produced under varied soil-moisture conditions, indicating a retardation of growth and fruiting activities during the late development of the large plants. Also there is included a discussion of the period of maturation for Pima bolls, data for the shedding of immature bolls, distribution and depth of penetration of the roots of Pima cotton, and other phases of the irrigation problem.

LOCATION AND PLAN OF THE EXPERIMENTS.

The investigations were conducted in a large commercial planting about 1 mile west of the Capitol Building, Phoenix, Ariz. The soil is a heavy clay loam in the first 18 inches, closely resembling adobe in properties. Beneath this is a layer of coarse sandy loam, which at a depth of 5 or 6 feet is interspersed with concretions of calcareous material.

Seed of the Pima variety of American Egyptian cotton was planted on April 5, 1919, on four 0.1-acre plats, which were separated from each other and from the rest of the field by substantial dikes. The plats were approximately 33¾ feet wide by 129 feet in length, so that 9 rows could be planted 3¾ feet apart.

When the plants were about 10 inches in height they were thinned by hand pulling to intervals of 12 inches. A string with markers attached was used to insure exactness of spacing.

For controlling the content of moisture in the different plats the "wilting coefficient," as defined by Briggs and Shantz (*9*),[1] was used as a basis for indicating the dates of irrigation. The term "wilting coefficient" of a soil is defined by Briggs and Shantz (*9*) as the moisture content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that

[1] The serial numbers (italic) in parentheses refer to "Literature cited," at the end of this bulletin.

soil first undergo a permanent reduction in their moisture content as the result of a deficiency in the soil-moisture supply. By permanent reduction is meant a condition from which the leaves can not recover in an approximately saturated atmosphere without the addition of water to the soil. The water in a soil in excess of its wilting coefficient is called the "growth water," or "available" water; that is, it is the portion available for the growth of the plants.

The plan of irrigation was as follows: Plat 1 was to be irrigated at such frequencies that complete exhaustion of the available moisture in the upper 2 feet of soil, as shown by moisture determinations, would never occur during the period of plant development. Plat 2 was to be irrigated shortly before the depletion of all available moisture in the upper 4 feet of soil, and plats 3 and 4 were to receive water when it was indicated that the content of available moisture in the upper 5 feet was near the point of exhaustion.[2] In irrigating, the water was to be measured by means of a Cipoletti weir and applied in such quantities that the content of "available" soil moisture in the upper 4 feet of soil of plat 1 would be increased to approximately 7 per cent, that of plat 2 to approximately 5½ per cent, and that of plats 3 and 4 to approximately 4 per cent. It had been determined by preliminary experiments that a flow of one-fifth of a second-foot for four hours would increase the moisture content of an acre of soil approximately 1 per cent to a depth of 4 feet. After cultivations were discontinued some difficulty was encountered in maintaining close checks between the quantities of water applied, as measured by the weir, and that shown by moisture determinations following the irrigation, it being difficult to secure deep penetration, but the quantities determined in the soil samples for the different plats were relatively the same.

To determine whether the supply of plant food might bear some relation to the water requirement, plat 4 was given an application of cotton-seed meal and 16 per cent acid phosphate in the drill at the rate of 500 pounds per acre by means of a 1-row cotton planter.

Under the plan of moisture control, irrigations were found to be necessary on the dates shown in Table I.

TABLE I.—*Irrigations of Pima cotton found to be necessary for moisture control.*

Plat.	First.	Second.	Third.	Fourth.	Fifth.
No. 1	June 10	June 26	July 28	Aug. 21	Sept. 2.
No. 2	do	July 28	Aug. 21	Sept. 2	
No. 3	June 26	Aug. 15	Sept. 2		
No. 4	do	do	do		

[2] The available soil moisture in a field of growing cotton is first exhausted in the superficial layers of soil and is gradually reduced in ever-increasing depths of soil until the roots are limited in their power of penetration or the action is retarded by the application of water to the surface layers.

Beginning on April 22, soil samples for moisture determinations were taken each week in foot sections to a depth of 6 feet.

Immediately after thinning, 20 normal plants were selected in each plat and designated as observation plants. To minimize the error which might result from soil variations, 5 plants were selected 29 feet apart in each alternate row, excluding the outside rows, thus locating the 20 plants on four alternate inside rows, so that each represented an area of approximately one two-hundredths of an acre.

Measurements of the growth of the main stem of these plants were recorded each week on the same day that moisture samples were taken. This was accomplished by measuring from an india-ink mark near the ground to the tip of the terminal bud. In planning the experiments it was decided that a detailed study of a few individual plants selected in the above-described manner and produced under different conditions of soil moisture and available food supply would be of greater service in providing a better knowledge of the water requirements of the crop than a cursory inspection of a large number of plants studied collectively.

Beginning with the appearance of the initial flower about June 30, the flowers on each of the selected record plants were marked with the date of opening, in order to determine the length of the development period of the boll and to obtain information in regard to shedding.

ADAPTATION AND LENGTH OF THE DEVELOPMENT PERIOD.

The Pima variety, which is the only kind of cotton now grown in the Salt River Valley, seems in many ways admirably adapted to the climate of that district. Thus far in the history of the industry there have been no very destructive insect pests or diseases to affect the yield on a large scale, and storm damages have been infrequent. Yields of a bale and more per acre have not been uncommon, yet the average yield for the whole producing area for several years has been less than one-half bale per acre. Some of the growers would attribute this low average to the comparatively long development period required by the Pima Egyptian crop. While other factors, such as the location of a part of the crop on poorly adapted soils and in the hands of inexperienced growers, undoubtedly are largely responsible for the low average yields, yet the length of season required is of no little importance in the greater part of the Salt River Valley, where comparatively early frosts have been responsible for serious damage to the late crop of bolls. This has been the case especially where heavy soils or delayed preparation made planting impossible before the middle of April. It has been estimated by some of the growers that the heavy frost of November 1, 1919, was responsible for destroying from 15 to 20 per cent of the bolls on about

half of the cotton acreage in the Salt River Valley. No estimate was made by the writer for the whole valley, but in several fields visited it appeared that from 30 to 40 per cent of the bolls had been destroyed. The variation in season from year to year will not permit any rigid rule to be fixed for a critical date of planting, and consequently mistakes are made in planting too early as well as planting too late. The prolonged period of frosts and low temperatures occurring in late March and early April, 1920, was responsible for very heavy loss to the cotton growers of the Salt River Valley on account of the poor stands which resulted.

The Pima cotton plant will continue to develop bolls during a long period when environmental conditions are favorable. The writer has observed flowers to be still appearing on plants which had commenced flowering 150 days previously. However, the normal period of flowering for the Pima variety in the Salt River Valley is from 90 to 110 days. Results by Ewing (*12*) in Mississippi and Lloyd (*19*) in Alabama show that the length of the flowering period in those States for Upland varieties is from 40 to 80 days. The flowering curves of Balls (*3*) show that in Egypt the flowering of Egyptian varieties continues through a period of 120 to 140 days, while flowering curves for Sea Island cotton in the West Indies as presented by Harland (*14*) show that the duration of the principal fruiting period there is from 140 to 150 days.

In Egypt Balls (*3*) places considerable importance on "the time of arrival" of the cotton crop; this is not so much because of frost damage as because of the injury resulting from "root asphyxiation," when the water table rises in late summer. After the flood season of the Nile, when the water table has been lowered, the flowering often revives and continues through October and into November. Harland (*14*) states that in the West Indies the time of arrival of the crop is not of practical importance. In Arizona the general tendency of the Pima variety is to continue flowering at a somewhat reduced rate throughout the month of September, but not infrequently many of the bolls set during this month are damaged or destroyed by early frosts.

The percentage of bolls set in September, 1919, which reached maturity on the heavy soil above described in which the seed was planted on April 5, was as follows: Plat 1, 51; plat 2, 40; plat 3, 39; plat 4, 41.

The period of maturation for bolls of Pima cotton, as derived from the data obtained by the writer during the season of 1919, is considerably longer than that given by any commercial variety reported to cotton literature. Ewing (*12*) gives the mean length of the boll-development period of small-boll Upland long-staple varieties in Mississippi as 51.5 days and for small-boll early varieties 48.5 days.

Balls (*3*) gives 48 days as the mean for standard Egyptian Mit Afifi at Cairo, and Harland (*14*) reports 51 days for the mean of Sea Island cotton in the West Indies.

The mean development period, as determined for 3,319 bolls of Pima cotton at Phoenix, Ariz., during the season of 1919, was 68 days. Results[3] obtained by Leding at Sacaton, Ariz., which indicated that the length of the period of development of the boll for the Pima variety during the season of 1918 averaged 67 days would seem to substantiate the above data as to the mean lengths of the development period. Mr. Leding's data also conforms to that of the writer in regard to the lengthening of the period as the season advances.

The lengthening of the period of development of the boll in the later months, as shown in Table II, is also in agreement with the results reported by Allard (*1*) and Ewing (*12*) in the Southern States, showing that the early bolls matured within a shorter period than the later bolls. While the climate of the Salt River Valley is reported to be similar in many respects to that of the Nile Valley in Egypt, it would appear from the reports of Balls (*3*) that no such lengthening of the boll period occurs there. Balls speaks, however, of the effects of environmental influence on the boll period and states that it is eight days longer in the Middle Delta than at Cairo. It is also apparent from the reports of Harland (*14*) that no such lengthening of the boll period occurs in the tropical climate of the West Indies.

From a study of the results shown in Table II, it would appear that there is no relation between soil-moisture conditions and the period of boll development. It also seems evident from the results shown in Table II that the heavy application of fertilizer containing 10 per cent of available phosphoric acid had little or no effect in hastening the maturity of the bolls produced on plat 4.

TABLE II.—*Monthly variation in the development period of the bolls of Pima cotton in 1919.*

Plat.	Average soil moisture during flower production (per cent).	Length of period (days) for flowers opening in—		
		July.	August.	September.
No. 1	5.0	55.8±0.14	69.5±0.30	80.4±1.76
No. 2	3.1	54.4± .18	68.3± .35	80.9±1.91
No. 3	2.5	53.2± .13	67.5± .30	85.4± .42
No. 4	2.8	53.2± .15	66.2± .30	81.1± .49
Mean temperature, °F		76.5	75.9	69.0

WATER-STRESS BEHAVIOR.

The irrigation on June 10 of plats 1 and 2 caused the plants in these plats to grow more rapidly than those in plats 3 and 4, which

[3] Unpublished. Kindly furnished to the writer for use in this bulletin.

did not receive their first irrigation until June 26. (Pl. I.) Throughout July and August the plants in plats 1 and 2 continued to grow more rapidly and exhibited a more luxuriant growth. This is shown in the diagrams in figure 1, which gives the growth in inches per plant per week and the average percentage of available moisture per week in the upper 4 feet of soil in each plat.

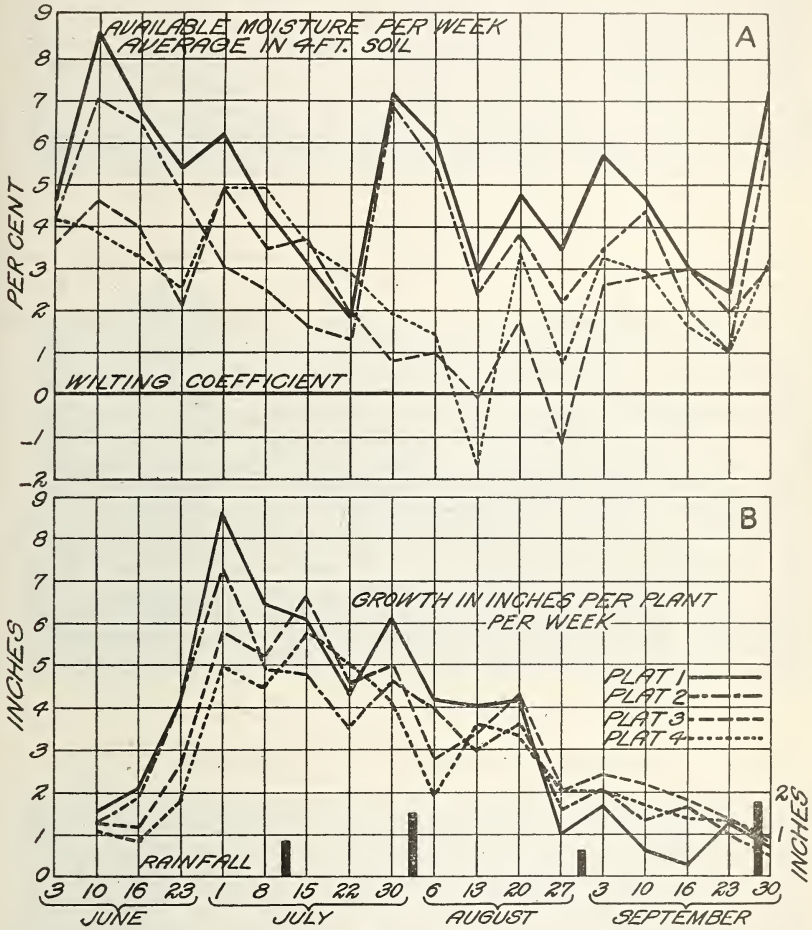


FIG. 1.—Average percentage of available moisture per week in the upper 4 feet of soil in four plats and the average increase in growth of the main stem of the plants per week.

During periods in the summer when very high temperatures were prevailing and when transpiration by the plant was at its highest, it was observed that the plants on plat 1 exhibited what might be termed a "water stress" in more pronounced degree than those on any of the other plats. This stress was made manifest by the wilted appearance of plants on plat 1, which occurred more frequently and

continued through a longer period during the day than on the other plats. Increasing the soil moisture in plat 1 was effective in preventing this wilting for only a short time. In six or seven days subsequent to an irrigation the plants would again show a loss of turgor of the leaves under the heat of the sun toward the middle of the day.

Balls (*3*), in considering the functions of the cotton root system, states that "since deficient water absorption is the real limiting factor in the sunshine effect, it follows that the size of the root system is the true limiting factor of water absorption and that the humidity of the soil may vary between wide limits without affecting it." In the effort to determine whether there was any difference in the root systems of plants on the four plats which might account in part for a deficiency in water absorption by the larger plants, excavations were made on March 1, 1920, and several plants were removed from the ground with all of the roots that could be traced in the upper 18 inches of soil. It was found that the roots had lived through the winter, and only a few of those uncovered showed any signs of decay. A count was made of all lateral roots attached to the 18 inches of taproot, a summary of which is given in Table III.

TABLE III.—*Count of lateral roots attached to top 18 inches of the taproot of Pima cotton in 1919.*

Plat.	Mean number of laterals.	Number of observations.
No. 1	34.6±1.56	13
No. 2	32.1±1.49	15
No. 3	24.4±1.08	17
No. 4	38.2±1.09	30

It is not a far-fetched supposition that the earlier irrigation received on June 10 by the plants on plats 1 and 2 would have encouraged the production of lateral roots near the surface of the ground and that the roots of plants not receiving early irrigations would have been forced to make their way into the deeper subsoil in order to obtain moisture, while the formation of laterals in the dry topsoil would have been somewhat suppressed. It appears from the results shown above that this did not occur. While a considerably greater number of laterals was found on plants from plats 1 and 2 than on those from plat 3, the greatest number of laterals was found on the plants removed from plat 4. It is not inconceivable that the liberal application of fertilizer supplied to plat 4 might have some bearing on the occurrence of this large number of surviving laterals in the topsoil, but until more detailed investigation has been com-

FIG. 1.—PLAT 1 ON AUGUST 10. IRRIGATED ON JUNE 10, JUNE 26, AND JULY 28.

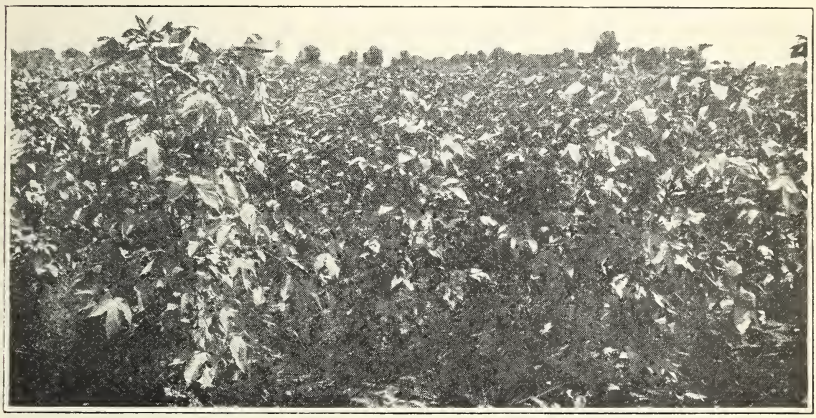
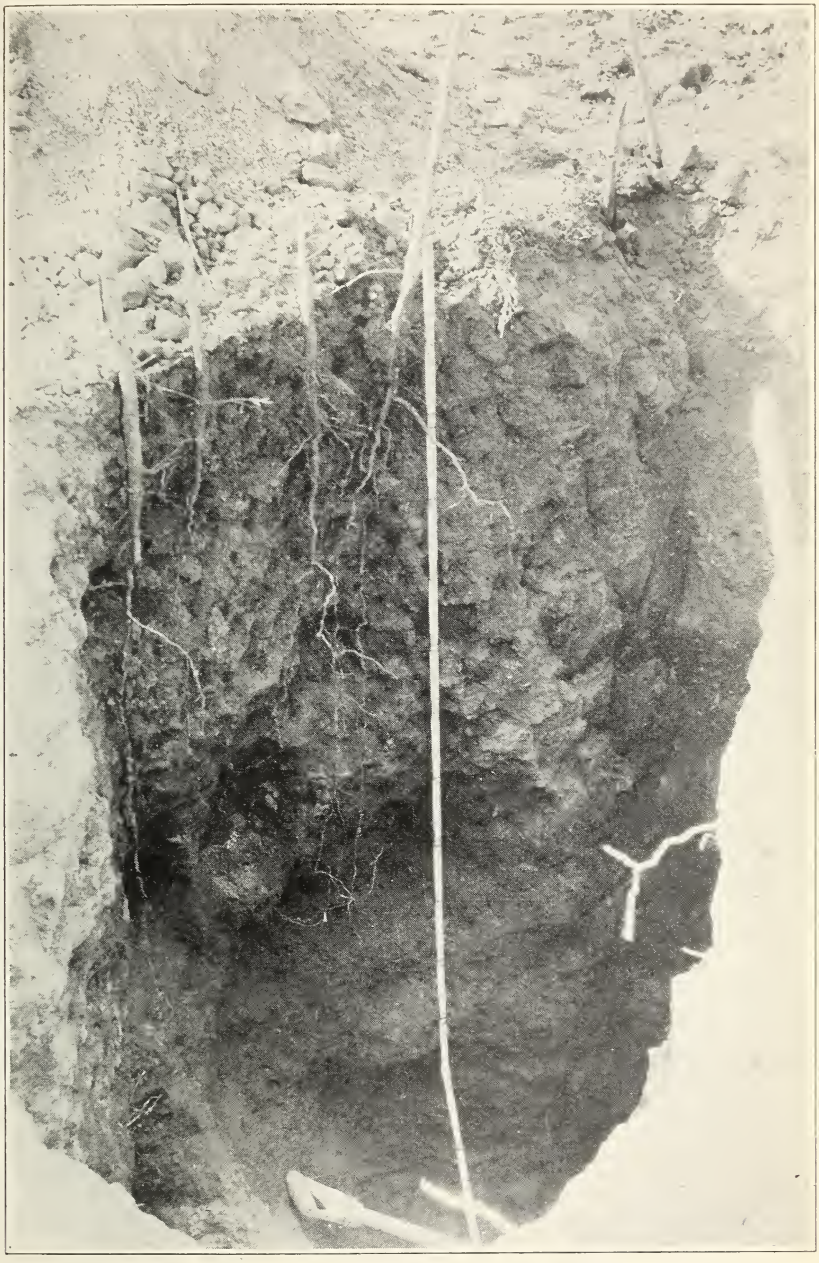


FIG. 2.—PLAT 2 ON AUGUST 10. IRRIGATED ON JUNE 10 AND JULY 28.

FIG. 3.—PLAT 3 ON AUGUST 10. LIGHTLY IRRIGATED ON JUNE 26. NOTICE THE CONTRAST IN THE SIZE OF LEAVES ON PLATS 1 AND 3.

PLATS OF COTTON IRRIGATED ONCE, TWICE, AND THREE TIMES.

A COTTON ROOT MEASURING 10 FEET 8 INCHES WHEN IN ITS NATURAL POSITION IN THE SOIL.



THE ROOT SYSTEM OF MATURE COTTON PLANTS.

A FIELD OF COTTON IRRIGATED IN ALTERNATE DEEP FURROWS FOR THE PURPOSE OF PREVENTING EXCESSIVE PLANT GROWTH ON HEAVY RICH SOILS.

pleted along this line it is perhaps unwise to enter into its further discussion.

Although realizing the experimental difficulties to be encountered in studying the root systems of the plants in their entirety, the writer attempted to trace some of the taproots to their maximum depth.

Hunt (*15*, p. 311) cites Bulletin 7 of the South Carolina experiment station (1892) as reporting that in sandy soils well-developed taproots were traced to a depth of 2 to 3 feet without coming to their end. Balls (*3*) states that "the greatest depth to which an unbroken taproot has actually been followed is 2 meters and 20 centimeters" ($7\frac{1}{4}$ feet). Effort was made by the writer and his colleague, Mr. J. Z. Richardson, to trace taproots to their greatest depth on all of the plats. Departing from the usual custom of removing soil from around the roots by means of a trowel and a jet of water, small hand picks were used. Success in reaching the tip of a taproot was met with only on plat 3. From a trench excavated 12 feet in depth near the side of the plants, a taproot was removed from this plat which had attained a depth of 10 feet 8 inches from the surface of the ground. (Pl. II.) On the other plats several taproots were followed to a depth of 7 or 8 feet, only to lose them when their direction departed considerably from the vertical. The tip of one secondary root was found on plat 1 at a depth of 7 feet, but there was nothing to indicate that most of the roots did not extend to a depth as great as those on plat 3.

Contrary to expectations and to statements in the literature of the subject, it was found that a great number of the secondary roots grew vertically downward in the soil after having grown obliquely for some distance. (Pl. III.) From all appearances the primary roots had performed their normal functions but were assisted by these deep-seated auxiliaries, which at considerable depth could not be distinguished from the primary roots. Upon considering that the plants were spaced only 12 inches apart and that during a part of the summer the water requirement for single plants was more than 3 pints a day, this extensive development of a deep root system does not seem surprising.

Upon examination of the roots it was found that there was little difference in the root systems of the plants from the different plats, either in distribution or in the size of individual roots. Caliper measurements were made of the diameters of all the roots which were studied. The measurements were taken on the lateral roots by applying the calipers about 4 inches from their point of attachment to the taproot. It was found that the mean number of lateral roots over one-eighth of an inch in diameter was 2.8, 2.7, 3.0, and 2.6 per plant for plats 1, 2, 3, and 4, respectively.

The taproots of the large plants were proportionately larger than those of the small plants to a depth of 10 or 12 inches below the surface of the ground, but at a greater depth than this they were not larger in diameter than those of smaller plants. Such data would seem to indicate that a limiting root system may have an important bearing on the water-stress behavior of the largest plants, it being a logical conclusion that the root system required for supplying the water demands of a large plant would be larger than that of a small plant.

In order to have additional data on this point, attention was next directed to the relative quantities of vegetative material produced on the different plats and to the demands made upon the moisture of the soil in supporting this material.

From the difference in the moisture content of the soil samples, which were taken at weekly intervals and also just before and two days following all irrigations, it was possible to compute the moisture lost from the soil during any week or month and for the entire period of development of the plants. The average quantity of water lost per acre each day (Table IV) was determined by dividing the weight of water lost from an acre during the entire month by the number of days in the month. The quantity of dry matter produced per unit area was determined by harvesting the plants when fully matured on an area of 900 square feet near the center of each plat. These samples, which included practically all of the dry matter produced above ground, were placed on canvas sheets and dried by the sun until they had reached a constant weight. Subsamples were then taken and dried at 110° F., and from these results the air-dried weights were corrected and taken to represent the average production of dry matter on the entire plat. The field water requirement was determined after the method of Briggs and Shantz (*10*), by dividing the total weight of the water lost from the soil during the whole period of growth by the total dry weight of the crop.

TABLE IV.—*Comparison of monthly water loss and dry-matter production by Pima cotton on plats 1 and 3 in 1919.*

Month, 1919.	Water lost per acre.				Dry matter produced per acre (pounds).		Field water requirement.	
	Inches.		Tons per day.					
	Plat 1.	Plat 3.	Plat 1.	Plat 3.	Plat 1.	Plat 3.	Plat 1.	Plat 3.
May	1.2	0.9	4.4	3.3	5,426	4,013	894.8	853.6
June	5.5	2.4	20.8	9.1				
July	5.6	4.5	20.5	16.5				
August	6.4	6.0	23.4	21.9				
September	2.7	1.3	10.2	4.9				

Table IV shows a striking contrast in the quantity of water used by the plants on plats 1 and 3 during May and June. The table also shows that during the month of June more than twice as much water was lost from plat 1 as from plat 3. The difference is all the more striking in view of the fact that the direct evaporation from the soil surface must have been less on plat 1 because of the shade afforded by the large plants (Pl. I). On July 8 the average height of plants in plat 1 was 7.5 inches greater than the average height of the plants in plat 3. Table IV further shows that, when calculated to an acre basis, plat 1 produced 1,413 pounds more of dry matter than plat 3. The water requirement (pounds of water expended per pound of dry matter produced) is shown to be about 5 per cent greater for plat 1 than for plat 3.

TABLE V.—*Comparison of the height of Pima cotton plants and the percentage of shedding on plats 1 to 4 in 1919.*

Plat.	Height, Sept. 1 (inches).	Total bolls shed prior to Oct. 1 (per cent).
No. 1	63	26.6
No. 2	55	21.5
No. 3	54	16.7
No. 4	50	17.8

WATER RELATIONS AND THE SHEDDING OF IMMATURE BOLLS.

From Table V it will be seen that the greatest percentage of shedding occurred on the largest plants growing in soil which constantly contained the greatest quantity of available moisture. Such an occurrence would seem to be at variance with that observed by many investigators who have studied the shedding of the Upland cotton plant.

Barre (*5*, p. 23–24) states that "lack of sufficient soil moisture is the principal factor in determining shedding." Ewing (*12*) concludes "that a deficient supply of soil moisture will result in excessive shedding." Balls (*4*) in reporting shedding studies with Egyptian cotton states that "shedding becomes abundant toward the end of the interval between irrigations and decreases directly after watering, but finally becomes excessive again when the water level is raised and the lower soil becomes saturated." Evidence, however, is not lacking that the water content of the plant itself may be an important factor in furnishing the stimulus for the shedding of squares and young bolls, and to the writer it appears significant that most of the investigators have proposed this factor as bearing an important relation to abscission. Harland (*14*) credits Nowell with the state-

ment "that shedding occurs when, from any cause whatever, the amount of water taken in by the roots falls short of that given out by the leaves." Ewing (*12*) reports from his observations that "it appears that the water content of the plant must have an important influence on shedding, and the water content is, of course, dependent on the amount of water absorbed by the roots and the amount transpired." Lloyd (*19*) concludes that "the water deficit is the cause of rises in temperature in the tissues, and this constitutes the stimulus which directly leads to abscission." Balls (*3*) has observed that "though the primary cause of shedding in Egypt is a deficient root absorption, it follows that an excessive transpiration rate must produce the same result, since the terms 'deficient' and 'excessive' are relative."

SHEDDING STUDIES UNDER ARIZONA CONDITIONS.

From the observations of the writer it appears that under Arizona conditions the severe water stress exhibited by plants possessing large areas of leaf surface and the shedding of squares and bolls are not always induced by a lack of "available" moisture in the soil. Such a conclusion may seem paradoxical in the light of general opinion, but to one who has studied the water relations of the cotton plant when grown under arid conditions it may not appear unreasonable. It is well known to plant physiologists that some plants are better provided than others with special structures for resisting too great a loss of water when growing under arid or desert conditions. The cotton plant seems to be one of the plants not so well equipped for reducing evaporation under arid conditions and frequently loses more water by transpiration than the roots can absorb from the soil. Recent work on the relations of plants to water supply, including contributions by Lloyd (*18*), Livingston (*17*, p. 216), Free (*13*, p. 114), Lyon and others (*20*), Coit and Hodgson (*11*), Balls (*3*), and others, had indicated that a feeding rootlet, by absorbing some of the soil solution with which it is in contact, creates a condition of instability which results in considerable film movement toward the drying-out zone. Undoubtedly it is the deficiency of this assumed property of capillarity in supplying the film moisture at a sufficient rate to replace the amount absorbed by the roots that accounts for the occurrence of water deficit in the tissues of the cotton plant, as shown so clearly in large plants with a great deal of transpiring surface. It is fortunately true that this deficit, occurring during the hours of hottest sunshine, is largely made up during the late afternoon and night, provided climatic conditions are not too stringent. When very dry hot weather occurs at a time when the soil conditions are unfavorable to the ready absorption of water by the roots, the shedding of immature fruits reaches its maximum.

It has been stated by both Lloyd (*19*) and Balls (*3*) that there is always observable a steady increase in the percentage or relative rate of shedding of squares and bolls as the season advances, the first squares formed having the lowest relative shedding rate and the highest rate occurring just before the plants begin to show a retardation of growth near the end of the season. Lloyd would explain this as probably due to the fact that the adjustment of the plant to its environment is not as good during the latter part of the fruiting season as earlier. Having observed the records of well water in which the water was gradually lowered during the summer and concluding therefrom that the moisture content was reduced in ever-

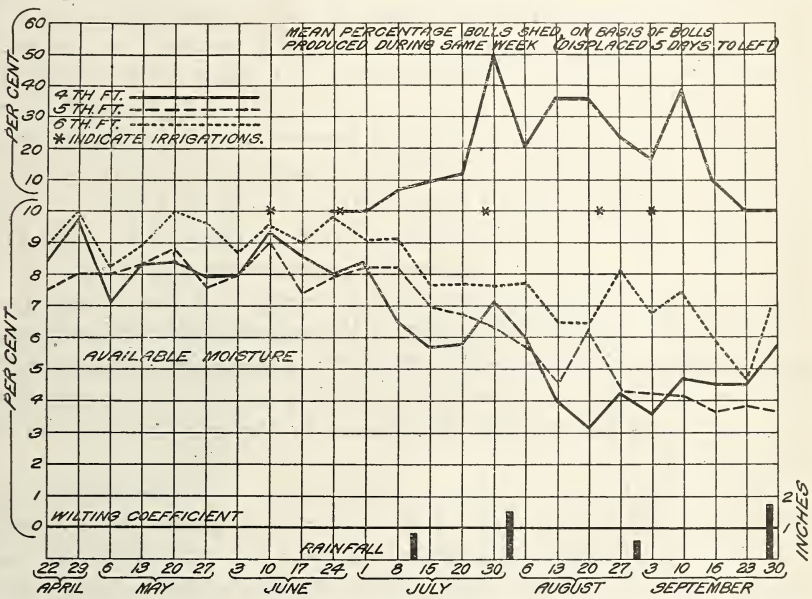


FIG. 2.—Moisture content of the deeper layers of soil and the mean percentage of bolls shed on the basis of the total bolls produced during the same week.

increasing depths of the soil as the season advanced, he reasons that this condition places a more severe tax on the plant and causes an increasing rate of shedding. Though Lloyd (*18*) presents no soil-moisture data to substantiate his hypothesis as to the relation of this factor to shedding, it appears from the results secured by the writer and confirmed by four years of observation of the water relations of the Egyptian cotton plant under arid conditions that Lloyd's opinion is well founded.

The amount of square shedding at Phoenix was so small at the commencement of the fruiting activities that no attempt was made to record the rate after the first three or four weeks. The curves representing boll shedding do not show the rate of shedding increasing with the advance of season to the marked degree exhibited in the curves presented by Lloyd. This, however, is not surprising when

it is remembered that Lloyd's observations were made under conditions where the soil-moisture content was increased only by rainfall, and this usually in such small quantities as to affect only the superficial layers of soil.

It will be observed from the curves of shedding (displaced) and of moisture content of the deeper layers of the soil as shown in figure 2 that there are indications of a correlation. Shedding began to increase coincident with the date (July 2) when the first important drop took place in the curve representing the moisture content of the fourth foot. Several years of experience in studying the subterranean conditions influencing the growth of the cotton plant have convinced the writer that the depth of the taproots and their rate of progress downward can be traced fairly accurately by means of frequent determinations of soil moisture. It seems evident from the curves that the roots had not reached the fourth-foot layer of soil in sufficient number to reduce the moisture content to any extent prior to July 2. Subsequent to this date, and especially following the reduction in moisture content of the fifth and sixth foot layers during this week, July 8 to 15, there was a rapid increase in the shedding rate. The increase was temporarily checked by the irrigation of July 28, which increased the moisture content of the fourth foot. Another node of high shedding rate followed soon after and continued until checked, evidently by the effect of the irrigation on August 21. The general trend of increasing shedding as the season advanced was finally checked in early September by the gradual cessation of plant growth.

That the depletion of moisture in the deeper soil is responsible for the increased shedding rate may be supported by other evidence noted in a different part of the Salt River Valley, where the water table has risen to within 5 or 6 feet of the surface, because of leaky canals, etc., and the soil is of a gravelly loam nature permitting the free movement of water. In this locality it was observed that cotton plants, although of large size, widely spaced, and having considerable transpiring surface, shed but few of their small bolls during the period when the shedding rate was highest in localities where the water table was not within reach of the cotton roots. In 1919 yields of a bale to the acre were not uncommon in this district, and one 7-acre field yielded at the rate of 1.7 bales of lint per acre. In other localities where the water table is still nearer the surface and where the soil has a greater capacity to retain moisture, it often happens that the plants grow to a height of 7 or 8 feet, and here the shedding is excessive as the season advances. This condition undoubtedly limits the roots which are functioning properly to a zone near the surface, and the strain imposed upon these roots by the great rate of transpiration apparently is a factor in the magnitude of the shedding rate.

THE PERIOD BETWEEN FLOWERING AND SHEDDING.

The interval between the opening of the flower and the completion of the abscission process is of some importance in identifying the stimulus which produces shedding. From Table VI it is apparent that there is little or no correlation between the length of this period and the moisture content of the soil at the time of flowering.

TABLE VI.—*Period of retention of shed bolls developing from flowers of Pima cotton blooming on successive weeks on four plats compared with the available moisture present in the soil during the season of 1919.*

Date.	Plat 1.	Plat 2.	Plat 3.	Plat 4.
July 16 ..... days	9.0	8.2	7.7	8.1
22 ..... do	10.8	10.6	6.0	10.7
30 ..... do	7.8	13.8	12.5	8.5
Aug. 6 ..... do	7.5	8.1	7.7	5.6
13 ..... do	9.2	8.0	12.0	10.1
20 ..... do	7.1	9.2	8.9	10.7
27 ..... do	9.4	9.0	10.4	11.8
Sept. 3 ..... do	16.1	16.5	15.1	12.0
10 ..... do	18.3	13.8	8.8	10.4
16 ..... do	10.6	9.5	6.1	10.0
23 ..... do	16.2	10.2	11.3	21.2
Mean	11.1	10.6	8.8	10.8
Mean available moisture in top 4 feet of soil ..... per cent	5.0	3.0	2.5	2.8

Ewing (*12*) states that "the period between flowering and shedding in general is longest when shedding first begins and shortest at the close of the season." Lloyd (*18*) shows that "there is little evidence that the mean of age frequencies of shed bolls was reduced during the season, but that there is definite evidence that the mean may recede or advance as a result of the additive or subtractive effects of stimuli, such as the additive effect of rain upon that of the soil moisture which resulted in a recession of the mean of three days." It appears from the results shown in Table VI that in Pima cotton there is a tendency for the period between flowering and abscission to increase as the season advances, under the conditions which obtained under this experiment, but the fluctuations were great even near the end of the season.

A study of the results in Table VI will show that there is only one weekly mean which exhibits clearly the effect of some stimulus operating generally on all the plats. This is the mean for the week ended August 6 when there was a recession of the mean on all the plats. It so happens that the only rain of any importance during the fruiting season fell on August 1 (fig. 2), so that there seems to be little doubt that rainfall was the responsible factor for the relatively large shedding of bolls during the week specified.

VARIATIONS OF PERIODICITY OF DEVELOPMENT.

The cotton plant, like many other plants, exhibits pronounced periodic variations in its developmental activity. Among these is the

period of hibernation, at the commencement of which the growth and fruiting activities gradually slow up and finally cease. Such behavior is considered entirely normal for the cotton plant, and it is commonly thought to bear a definite relation to the seasonal fall in temperature. A survey of the literature on the cause of such behavior reveals the presence of two widely diverse opinions, one of which views the cessation of activity as a direct response to changing external conditions and the other as the result of fixed, hereditary, internal causes. In the West Indies, where the tendency of the Sea Island cotton is toward perennial habits, the flowering curves as presented by Harland (*14*) show that a period of cessation in activity occurs about 90 days after the appearance of the first flower. After this, there is renewed activity and another distinct node is produced in the flowering curves. Balls (*3*) shows by growth and flowering curves that in Egypt there are remarkable differences between different strains of cotton grown under similar environmental conditions in respect to the time when growth and flowering cease. In discussing the phenomenon of cessation of activities he applies to it the term "senescence" and ascribes it to self-poisoning. He postulates that the influence is of a chemical nature, a thermotoxy local in and peculiar to the growing point.

From figures 1 and 3 it appears that in Arizona there may be variations in periodicity in the same strain, planted at the same time, grown in the same type of soil, and with all other conditions similar except soil-moisture content. This is noticeable during the later development of the plants when the transition from full activity into a condition of hibernation is taking place. It will be observed that until about August 20 the increase in growth per week was influenced by a proportionate amount of moisture present in the soil. After this date there was a more distinct slowing of the growth rate of plants on plats 1 and 2 than on the other two plats. This occurred despite the fact that the amount of soil moisture in plats 1 and 2 was greater than in the other two plats.

Balls (*3*) states that "when dealing with most pure strains, we find considerable uniformity in the date of the first flower. The stunted plants, if any, flower late, so that a close correlation here exists between the height of the young stem and the flowering date." However, in this connection he states that "all the plants of some strains in the author's possession (notably King Upland) come into flower almost simultaneously, even if some are stunted." In the writer's experiment, while there was a difference in the average height of the plants on the different plats at the time when flowering began, about June 30, there was a decided uniformity in the time the first flowers appeared. Though the average height of plants on

plat 4 at that time was only 17.5 inches, as compared with 25.7 inches as the average height of the plants on plat 1 (fig. 1, *B*, and Pl. I), it could hardly be stated that the former plants were stunted. At that time they were growing in a satisfactory manner, and apparently the supply of soil moisture was ample for their need.

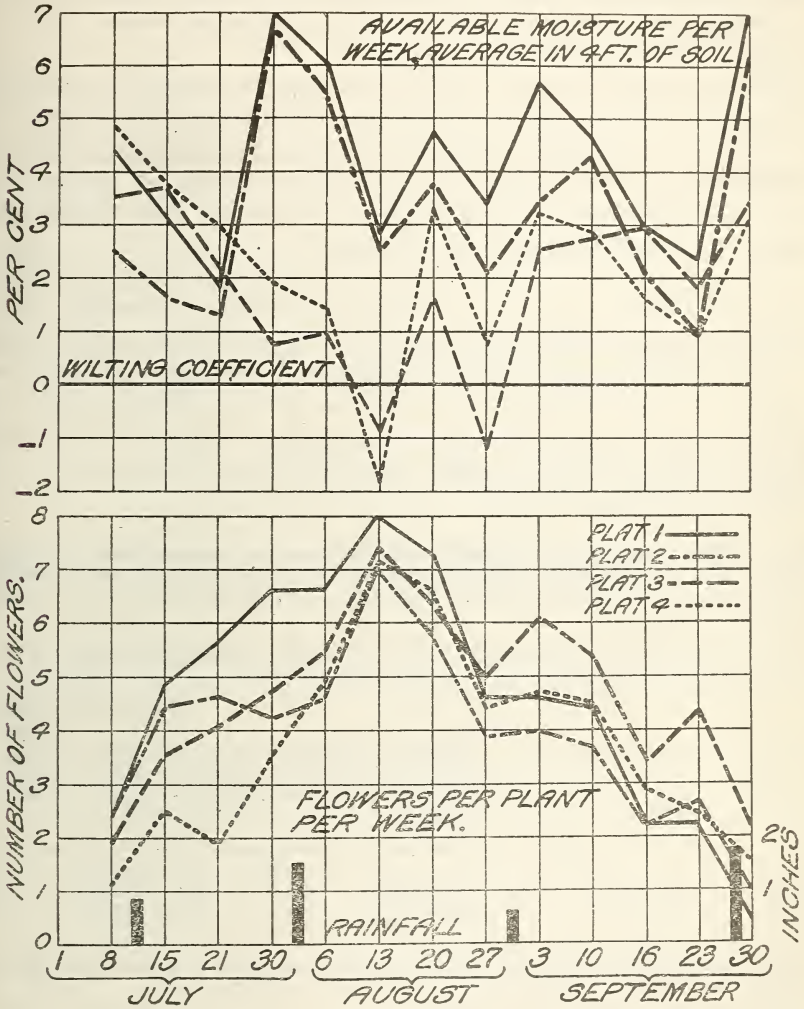


FIG. 3.—Average percentage of available moisture per week in 4 feet of soil and the weekly flowering curves of four plats.

Figure 3, *B* shows that the flowering rate of the plants in plat 1, which were growing at a more rapid rate than those of plat 3 (fig. 1, *B*) during July was greater than plat 3, but did not continue at the same relative rate later in the season. During the week August 20 to 27, the rate of flower production in plat 3 became equal to that

in plat 1. Following this week the plants in plats 1 and 2 were never so responsive to the influences which affect flowering as those in the other plats, and their curves dipped with considerable regularity after September 3 to a condition of almost complete cessation about September 30. The curves of plats 3 and 4 also dipped toward a hibernation period, but with greater fluctuation and a greater amount of flower production.

It will be observed that during this period of gradual cessation in flowering the different plats held about the same relative position in regard to the moisture content of the soil as at the beginning of the flowering season, plat 2 having usually the second highest and the moisture content of the other two plats having been almost constantly smaller than that of plats 1 and 2.

Data given in Table VII indicate that some economic importance may be attached to such an occurrence, especially in seasons when the first killing frost of the autumn does not arrive earlier than is commonly expected for the vicinity. A summary of the data obtained by the Weather Bureau shows that the average date of the first killing frost at Phoenix, Ariz., during the years 1895 to 1920 is December 3, or 33 days later than the date on which cotton was killed by the frost in 1919.

TABLE VII.—*Comparison of flowers produced and stem growth prior to August 15, plants producing vegetative branches, bolls produced on 20 plants during September, and September bolls destroyed by frost on four plats of Pima cotton in 1919.*

Plat.	Percentage of—				Bolls produced on 20 plants during September.
	Total flowers produced during first 45 days beginning with initial date of flowering.	Total stem growth produced prior to August 15.	Plants producing vegetative branches.[1]	September bolls destroyed by frost.	
No. 1	60.5±0.97	85.3	5	49±2.2	263
No. 2	58.6±1.01	80.4	40	60±2.3	215
No. 3	48.9±1.00	76.2	10	61±1.8	340
No. 4	46.8±1.08	76.9	10	59±2.1	264

[1] Most of the vegetative branches made only a rudimentary development. The flowers produced were so few as to have no material effect on the flowering curves or the final yield.

From the data in Table VII it is apparent that plats 1 and 2 would have produced considerably more cotton per plant despite the early frost had the later flowering continued at the same rate as that on plats 3 and 4. The relative production of both stem growth and bolls was considerably greater during the first 45 days of the flowering season on plats 1 and 2 than on plats 3 and 4. This may be attributed to the fact that plats 1 and 2 received their first irrigation 16 days earlier than plats 3 and 4.

It will be seen from Table VIII that the greatest number of flowers per plant was produced on plat 1, to which the greatest quantity of water had been added. However, on account of the greater amount of shedding on this plat there was a smaller number of bolls set by October 1 than on plat 3, which had received the least water. The "potential seed-cotton production" on October 1 of plants on plat 3 exceeded that of any other plat, but the "potential seed-cotton production" is not in accord with the actual production, as determined upon picking. This discrepancy can be accounted for by the records of frost damage to bolls, as shown in Table VII, the percentage destroyed having been greater in plat 3 than in plat 1. Bolls set late in September were not able to develop fully, and those which cracked open sufficiently to be picked were lighter in weight than those set earlier in the season.

TABLE VIII.—*Comparison of the flowers produced, the percentage of shedding, the bolls set, and the potential seed-cotton production in each of four plats of Pima cotton with the total yield of seed cotton per acre in 1919.*

Plat.	Mean number of flowers produced.	Mean percentage of shedding.	Mean number of bolls set by Oct. 1.	Mean potential seed cotton produced (grams).[a]	Yield of seed cotton per acre (pounds).
No. 1	58.2±1.79	26.5±0.38	43.1±1.71	106	1,602
No. 2	50.9±1.78	21.6± .34	40.0± .40	96	1,437
No. 3	57.0±2.16	16.7± .21	47.6±1.89	111	1,496
No. 4	48.2±1.30	17.8± .26	39.7±.36	95	[b] 1,397

[a] Mean "potential seed-cotton production" in the sense here used is the mean weight of seed cotton per boll as determined upon picking, multiplied by the mean number of bolls set per plant on Oct. 1.
[b] The presence of a "slick spot" of approximately 900 square feet in plat 4 was responsible in part for the low yield on that plat. This soil variation was not noted until its presence was indicated by the stunted condition of the plants.

Such data, Tables VII and VIII, seem to indicate that every precaution should be taken in growing cotton in areas where there is danger of damage from early frosts to stimulate the setting of fruit to the fullest extent during the months of July and August. The data show that the first irrigation on June 10 was not so early that it produced an excessive number of vegetative branches but served the purpose of stimulating the plants into early fruiting, which was especially important for that particular season. The 16 days lost by the plants in plats 3 and 4 in the early processes of fruit production was a handicap that they never overcame. While the cessation of growth and flowering immediately after the 1st of September might result in a reduction of the yield, such loss of time under Salt River Valley conditions would hardly result so seriously as an equal length of time lost at the beginning of the fruiting season.

The more pronounced slowing in late summer of the growth rate and flowering of cotton plants which had produced a heavy growth of vegetative material early in the season presents a very interesting physiological problem. The work of some recent investi-

gators (Klebs, *16*, and Appleman, *2*) in being able to maintain almost any plant in continuous growth throughout the entire year would seem to indicate that the importance of periodicity has been exaggerated.

It is difficult to interpret the behavior of Pima cotton as above described on the basis of an inherent periodicity, but it is not improbable that physiological reactions are involved. It is a common observation among growers that cotton plants once stunted by water shortage are much slower in response when water is finally applied than plants which have not been so severely checked. A case of this nature came under the writer's observation at the Sacaton station in 1920. Plants growing in a sandy soil showed visible distress from water shortage about two weeks before the first application of water on July 7. In response to this irrigation the plants grew only 9 inches in height during the ensuing three weeks and required two additional irrigations before complete recovery, while plants on adjoining plats, which had shown no water stress, grew 14 inches during the three weeks following the first irrigation and responded promptly to each subsequent irrigation by making additional growth. The fact that all external factors except soil moisture were closely alike for all the plants in these experiments and that there was a distinct difference in the promptness of response to this particular factor gives probability to the interpretation that the cause is internal, but is subject to remedy by control of the external factors.

When we come to consider the adoption of means for remedying this maladjustment of the plant to its water supply, the most practical line along which to work seems to be in modifying the conditions of the subterranean environment. The need for some such corrective measure seems especially imperative when dealing with heavy rich soils which cause a quick and vigorous response of the plants to irrigation water when applied by conventional methods.

An experiment was conducted in 1919 by the writer and his cooperator, Mr. Warren H. Parker, in adjacent plats to those above described, in the effort to effect more perfect control of the plant growth.[4] The plants were grown in pairs of rows, with a wide middle 5½ feet between pairs and a space of 3½ feet between rows. The water was run in deep furrows made in the wide middle (Pl. IV), while the narrow middles were left dry after the planting season. The effect of the water when applied under these conditions was not noted in the behavior of the plants until five or six days later, and

[4] A double-row method of planting and irrigating Egyptian cotton has been outlined in connection with the single-stalk method of suppressing the vegetative branches, and tested in recent seasons at the United States Experiment Farm at Bard, Calif., near Yuma, Ariz. (*6, 7, 8, 21*).

the moisture content of soil samples taken in juxtaposition to the plants 24 hours after the application of water showed no increase above the fourth-foot layer but marked increase in the fifth-foot layers. The plants grown under this method of irrigation in 1919 behaved in a very satisfactory manner and did not show the marked slowing up of the growth and flowering rates late in the season exhibited by the plants on plats 1 and 2. In 1920 this method of irrigation on heavy soil was adopted commercially by Mr. Parker and proved very satisfactory. The plants which were irrigated at approximately 10-day intervals during the principal fruiting season fruited very heavily, with little loss from shedding, and the total yield per acre was considerably greater than had been obtained on the same soil in several years previously. The encouraging results obtained in these tests with a double-row method of cotton culture and reports of frequent successes in tests with a somewhat similar method at the Bard station point to the need of further experiments along this line. There seem to be possibilities of solving several important problems of cotton culture under irrigation by perfecting some such method.

CONCLUSIONS.

This bulletin reports the results of an investigation of the behavior of Pima cotton when grown under different conditions of soil moisture and available plant food in the Salt River Valley of Arizona in 1919.

The normal growing season in the Salt River Valley, while usually ample for substantial yields, is none too long for the complete development of the Pima cotton plant, and precaution on the part of growers is necessary in selecting a proper date for planting and to keep the plants in full activity during the limited time available for boll production. The occurrence in some years of heavy frosts about November 1 has occasioned considerable damage to the late crop of bolls.

The mean period of maturation for over 3,000 bolls of Pima cotton was 68 days.

In Arizona early bolls mature within a much shorter period than later bolls. The mean difference in time required for maturation between bolls developed from flowers blooming in July and those blooming in September was 27 days.

Plants which had produced the greatest quantity of vegetative growth appeared to suffer most frequently from "water stress," remaining longer in a wilted condition between irrigations and showing an earlier recurrence of wilting after irrigation.

The fact that there was no appreciable difference in size or distribution between the roots of large plants and small plants seems to

indicate that a limiting root system may have an important bearing on the water-stress behavior of the largest plants.

Most of the taproots of both large and small plants extended to a depth greater than 7 feet, and the only one followed to its greatest depth measured 10 feet 8 inches in length. A considerable number of secondary roots extended to great depths and apparently shared the function of the taproot.

The greatest quantity of water was removed by the plants in plat 1, where the moisture content of the soil had been kept highest throughout the season, the amount removed during May and June being about twice as much as in plat 3. Plat 1 produced dry matter at the rate of 1,413 pounds per acre more than plat 3.

It appears that in Arizona the severe water stress frequently exhibited by plants possessing large areas of leaf surfaces and the shedding of squares and bolls from such plants are not always induced by a lack of "available" moisture throughout the soil mass, but may be due to a reduction of moisture in the portion of the soil immediately surrounding the roots more rapidly than it can be restored by capillarity.

There appears to be an important relation between the increase of the shedding rate (based on the number of bolls available for shedding) during the first two months of the flowering season and the gradual reduction of the moisture content in the lower soil layers.

The mean interval between the opening of the flower and the completion of the shedding process was approximately 10 days. The general tendency was for the period to increase as the season advanced, but fluctuation was great even near the end of the season.

A heavy rain materially shortened the interval between flowering and shedding.

In late summer a depression in the rate of growth and flowering was shown in the large plants much earlier than in the smaller plants. After this retardation began the large plants never again exhibited as prompt or vigorous a response to irrigation as the smaller plants.

Plants to which irrigation water was supplied soon after the first flower buds began to form, and frequently thereafter, produced a greater stem growth and a greater number of flowers during the first 45 days of flowering than plants to which water was not supplied until 16 days later.

Plants growing in soil which was supplied with water sparingly throughout the season produced a greater number of bolls late in the season than plants provided with larger supplies of soil moisture.

The highest "potential seed-cotton production" per plant by October 1 was on plat 3, which had been supplied with water sparingly.

The highest actual yield of seed cotton was produced on plat 1, on which the plants had been stimulated by comparatively early irriga-

tions to set more than half of their total number of bolls during the first half of the flowering season.

The data indicate that effort should be made to stimulate the setting of fruit to the fullest extent during the months of July and August, especially in areas frequently visited by comparatively early frosts, since the number of bolls set during this period largely determines the extent of the crop.

There are indications that an internal physiological reaction results from prolonged water stress in the plant tissues which tends to inhibit their response and recovery when more favorable conditions are restored during later development.

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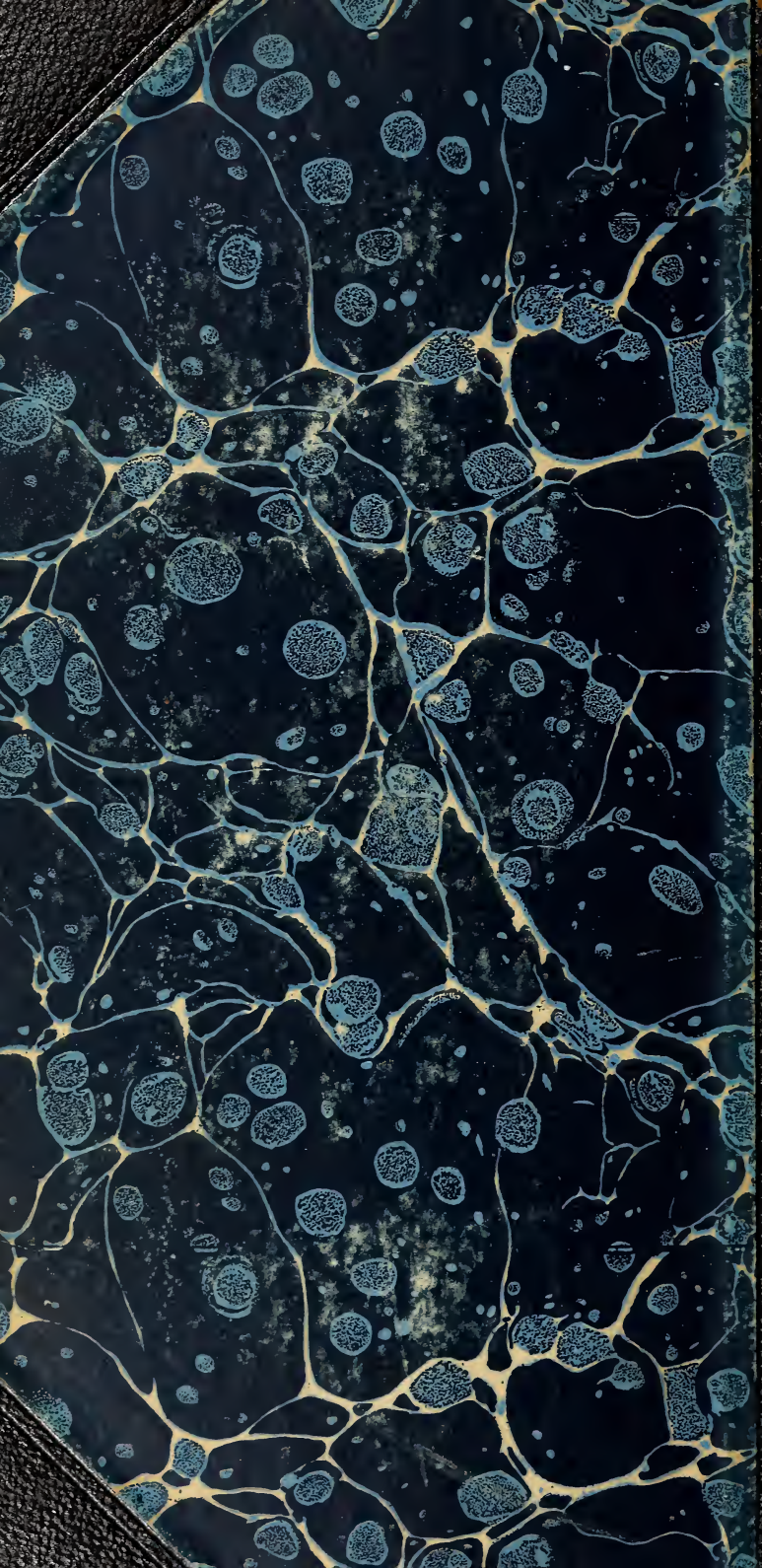
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